# Target Search & Selection for the DI/EPOXI Spacecraft

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**Upon completion of the Hartley 2 flyby in November 2010, the Deep Impact (DI) spacecraft resided in a solar orbit without possibility for gravity assist with any large body. Conservative estimates of remaining fuel were enough to provide only an 18 m/s impulse on the spacecraft. We present our method and results of our systematic scan of potential small body encounters for DI, and our criteria to narrow the selection to the asteroid 2002 GT as the target flyby body. The mission profile has two deterministic maneuvers to achieve the encounter, the first of which executed on November 25, 2011.**

## I. Introduction

In an extension to the Deep Impact[1] (DI) mission, EPOXI[2] (Deep Impact Extended Investigation and Extrasolar Planted Observation and Characterization) successfully executed a flyby and observation of the comet Hartley 2 in November, 2010. The flyby left the spacecraft in a 0.98 x 1.22 AU solar orbit, where the nearest ballistic encounter with any large body over the next ten years would be 20 Mkm of Earth. As for the remaining fuel, the most conservative estimates where roughly 2 kg of hydrazine, amounting to a meager 18 m/s in total $\Delta v$. A mission to another comet or asteroid might require up to 1 m/s for pointing and momentum wheel desats, in addition to 1-2 m/s for course corrections, as well as 4-10 m/s for terminal guidance. Thus, for the most conservative fuel estimate, the maximum deterministic $\Delta v$ possible was 12 m/s. Sending the spacecraft somewhere may require many years for a tiny maneuver to significantly alter the trajectory. The spacecraft must be capable of surviving the long flight, a tall order for an aging spacecraft that's already completed its extended mission and is five years past the primary mission.

With the remaining propellant the DI spacecraft might be capable of visiting another near-Earth object (NEO), a solar system body with perihelion less than 1.3 AU. To date, there are over 10,000 known NEOs, where approximately 1,000 of the objects were discovered just this last year. The ephemeris for most of the bodies is not known to sub-100,000 km accuracy and is constantly being updated when new information is reported. Considering the number of NEOs, one might be inclined to think that there are many options available for the DI spacecraft, but in the next 10 years, DI only passes within 10 Mkm of less than 5% of the objects. We found that smaller close approach distances (CAs) do not necessarily translate to smaller $\Delta v$s when the body is targeted, and CAs larger than 10 Mkm may even yield a lower $\Delta v$ cost. Targeting the objects by casting a broad net around all bodies with distant CAs is also challenging from an optimization standpoint. Since the $\Delta v$ available is so small, the strategy used to design the maneuvers must include high-fidelity integration for the spacecraft's trajectory. It must be capable of allowing maneuvers to appear anywhere along the trajectory as necessary, and with a good chance of locating the globally optimal solution. Given a list of targeted bodies that meet the stringent requirements for $\Delta v$, other aspects most be considered to decide the eventual target. Although a longer flight time is expected for this mission, minimizing the flight time is still important. Furthermore, the ephemeris for the body chosen to visit must be known with a high degree of certainty, since there is no propellant to steer the spacecraft off-course if necessary. The flyby geometry must be navigable, with reasonable relative velocities, and the trajectory cannot be too sensitive that it requires more statistical $\Delta v$ than available. The size of the body is also important in determining whether or not to visit the NEO, and after all, there must be a scientifically compelling reason to send the spacecraft there.

In this paper, we describe in detail how we dealt with each of these challenges to arrive at the asteroid 2002 GT as the target flyby body. We show that in the next ten years, the maximum reachable distance for DI is less than 15 Mkm. Then, using the JPL Horizons[3] small-body database to generate the most accurate ephemeris to date, all the NEOs are scanned over a ten-year window for CAs inside of 15 Mkm. The CAs are targeted with multiple

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independent mission design softwares, MIDAS[4] and Mystic[5], and the results are tabulated by $\Delta v$. Since the primary objective of the mission is imaging, the geometry of the approach, flyby, and departure are critical. Furthermore, the spacecraft itself has constraints that dictate which encounter geometry is preferable. From a handful of options that are feasible from a $\Delta v$ point-of-view, in this paper we describe the various constraints and discriminators we used to choose the eventual target.

## II. Description of Spacecraft & Previous Missions

The DI mission was selected by NASA's Discovery program in July, 1999. The purpose of the mission was to investigate the comet surface and interior of Tempel 1 by means of an impactor, and to gain a better understanding of how craters form. The Delta II rocket launched DI from Cape Canaveral, Florida on January 12, 2005, and the impactor successfully collided with the comet Tempel 1 on July 4, 2005, completing its primary mission.

### A. DI/EPOXI Spacecraft

The primary mission consisted of two mated spacecraft: a 650-kg flyby spacecraft (Flyby) and a smaller impact spacecraft (Impactor). Both spacecraft were built by Ball Aerospace, with some components manufactured in-house at JPL. Here we provide a brief description of Flyby which is still in operation, and the focus of this paper.

A schematic of the spacecraft is provided in Figure 1. The spacecraft is three-axis stabilized by four reaction wheels. As shown in Figure 1, the spacecraft has one high-gain antenna (HGA) and two low-gain antennas. The HGA is two-axis gimbaled with a 1-m dish, and communicates with ground-stations on Earth via X-band radio transmitted at 8 GHz. The spacecraft is powered by two fixed solar panels arranged in a side-by-side configuration as seen in the diagram. The total area of the panels is 7.5 $m^2$ and they provide 620 W to the spacecraft at 1 AU. There is also a small 16-Ahr Ni-$H_2$ rechargeable battery for powering during solar eclipses. There are two

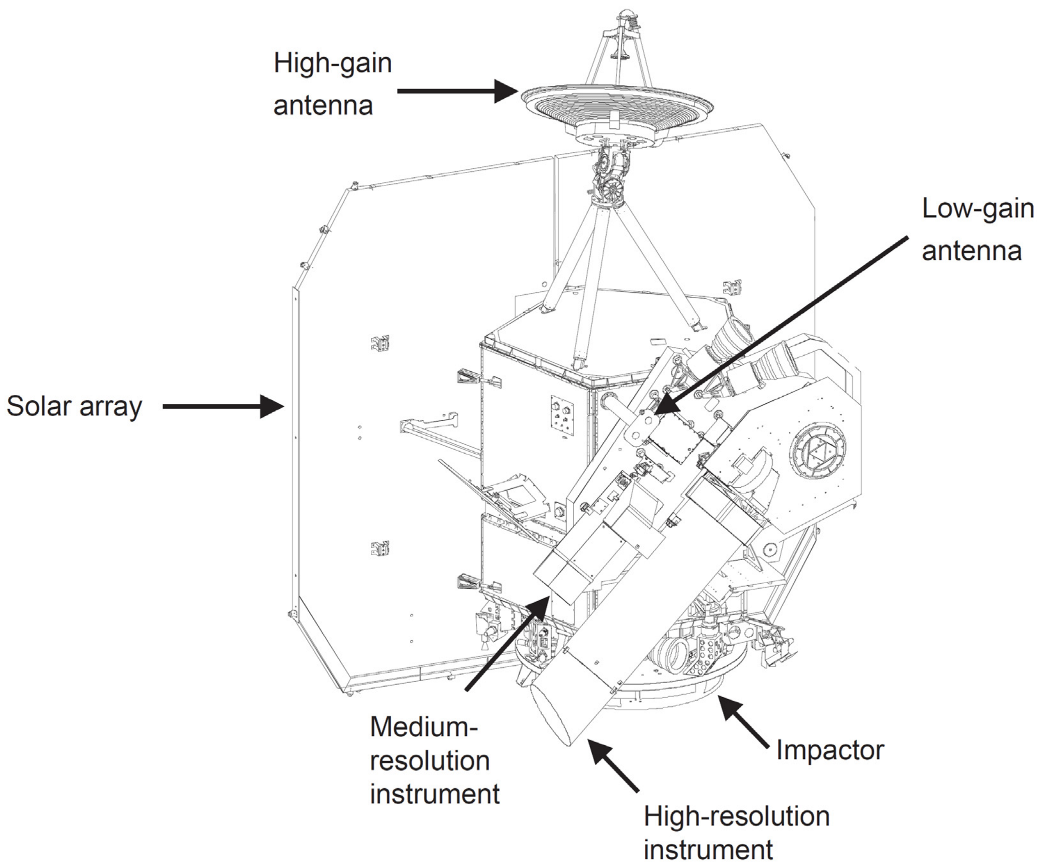


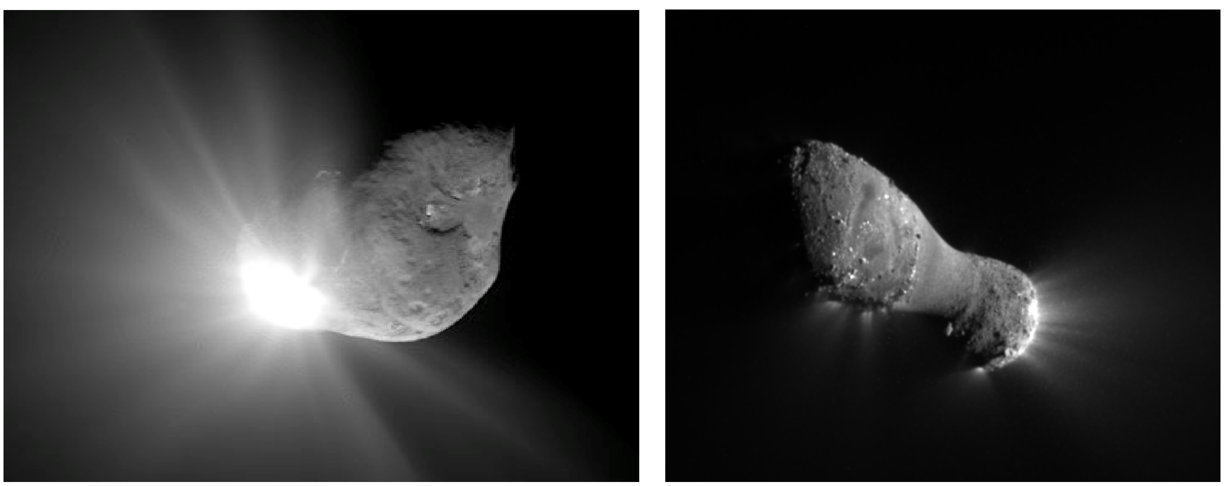

**Figure 1. The DI Spacecraft, Dimensions: 3.2 m x 1.7 m x 2.3 m.[1]**

computers onboard, as well as four hemispherical resonator gyros, and two star-trackers. Most of the spacecraft components are redundant, and switching to the back-ups is automated. For maneuvering, the spacecraft has a group of 5,000 N-s RCS thrusters, originally capable of providing a total impulse of 190 m/s from 85 kg of hydrazine propellant.

The High Resolution Instrument (HRI) is one of two imagers onboard, and contains a 30-cm diameter telescope that feeds to a multispectral camera and an IR spectrometer. The HRI camera has a field-of-view (FOV) of 0.12 deg with a resolution of 1.4 m/pixel at 700 km, and is one of the largest ever to fly on an interplanetary mission. The FOV for the IR spectrometer varies from 0.29-1.45 deg, depending on the resolution. The other imager, or the Medium Resolution Instrument (MRI), is primarily used for navigation. The MRI has a much smaller telescope (13-cm diameter) with a wider FOV of 0.59 deg, and capable resolutions up to 7 m/pixel at 700 km.

### B. Primary Mission to Tempel 1

As previously mentioned, the DI mission consisted of two spacecraft. The Flyby carried all the observing instruments, fuel for the combined spacecraft to reach Tempel 1, and the main telecommunications equipment to communicate with Earth. As shown in Figure 1, the Impactor was mated to the Flyby and carried a single camera, the Impactor Targeting Sensor (ITS), which was identical to the MRI. Also onboard was fuel needed to guide the Impactor to the target site once released from the Flyby. The combined spacecraft was targeted to hit the comet with a series of maneuvers, the last of which was executed 30 hours prior to encounter. At Encounter (E) - 1 day, the impactor was released; subsequently, the Flyby executed a divert maneuver such that it would flyby the comet at an altitude of 500 km. The Impactor then used its onboard autonomous navigation system (AutoNav) to guide itself to a location on the comet.[6] The Flyby used the same AutoNav system as on the Impactor to track the nucleus during its encounter, and successfully imaged the impact event and returned the images to Earth, thus completing the primary mission (Figure 2(a) shows the impact as seen from the HRI).



(a) (b)

**Figure 2. Images from (a) Imapactor at Tempel 1, July 4, 2005 and (b) Hartley 2 Flyby, November 4, 2010.**

### C. Extended Mission: EPOXI Mission to Flyby of Hartley 2

Following the DI mission, the Flyby spacecraft was fully functional and had approximately 70 m/s of propellant remaining. Thus, a maneuver was performed in August 2005 to put the spacecraft on a trajectory which would eventually lead to an encounter with comet Boethin. In mid-2007, NASA formally approved an extended mission for DI, called EPOXI, which included a flyby of Boethin. However, in the fall of 2007, efforts to observe Boethin using ground telescopes failed, leading to the conclusion that Boethin had disintegrated. A new target was found, comet Hartley 2, and the spacecraft was redirected towards it, with the goal of capturing high resolution images of the nucleus with the MRI and the visible and IR spectrum from the HRI. The trajectory to Hartley 2 took three years and included three Earth Gravity Assists to achieve the flyby.[2] The final Earth flyby took place in June 2010 and set the spacecraft up for the encounter on November 4, 2010. As was done for Tempel 1, the onboard AutoNav system was used during the flyby to track the nucleus through closest approach.[7] The system performed as expected, and images of the comet were successfully returned. Figure 2(b) shows the nucleus of Hartley 2 at the closest approach distance of 700 km.

## III. Mission Opportunities

Following the Hartley 2 flyby, the DI spacecraft resided in a 0.98 x 1.22 AU solar orbit, and inclined 0.056 deg to the ecliptic. (See Figure 3.) The period of the orbit was roughly 1.15 yrs. In Figure 4, the trajectory is plotted in an Earth-centered frame where the Sun-Earth line is fixed. As reported in the figure, there are two very distant passes with Earth, both occurring in 2018. However, neither passage is low enough to target Earth with the remaining $\Delta v$ for a gravity assist.

The two main drivers in searching the NEOs for potential mission opportunities are flight time and $\Delta v$. Unfortunately, there was some difficulty determining precisely the amount of hydrazine left on the spacecraft. According to one method for estimating the fuel based on instruments, the remaining propulsive $\Delta v$ was 34 ± 13 m/s. A different method yielded a more conservative estimate of 18 m/s. Additionally, at least 6 m/s of this would be required for spacecraft pointing, momentum wheel desats, course corrections, and terminal guidance. Allowing for enough time for a small propulsive maneuver to alter the trajectory, we scanned for all possible encounters for DI over a ten-year period that required less than 12 m/s in deterministic $\Delta v$.

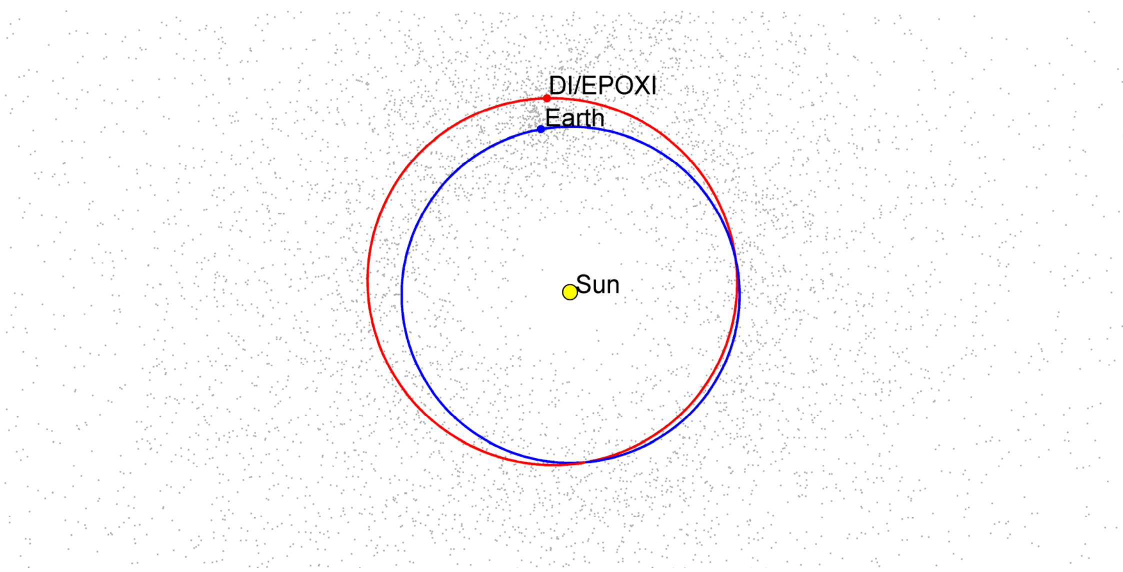



**Figure 3. Sun-centered, Inertial View of DI and NEOs, Positions on January 1, 2011.**

### A. Scan of NEOs

Searching through all known NEOs for favorable CAs is a numerically intensive process. Since the ephemeris for NEOs is constantly changing, it is desirable to automate the procedure to scan for close approaches. Scripts were written that query the Solar System Dynamics database for objects with perihelion less than 1.3 AU. As of August 19, 2010, the JPL Horizons database recorded 10,302 NEOs (8,080 asteroids, 2,222 comets). Ephemeris for the bodies is generated by propagating their trajectories with Horizons. The Horizons high-fidelity propagation is very accurate, including, for example, the effects of outgassing for the comets. To update the ephemeris for the NEOs, at any given time the scripts can query if new bodies have been discovered, or if JPL has received new information about a known asteroid or comet, upon which the ephemeris for the object is regenerated.

A close approach occurs when the distance between two objects is a minimum. We used two independent in-house JPL mission design software to compute the CAs: ENCFIND and Monte. In general, we found good agreement between the software, the only discrepancy being that ENCFIND sometimes computed extraneous roots. Our first scan of the NEOs turned-up 250 different objects with distances less than 7.5 Mkm, none of which belonged to the asteroid 2002 GT. In an effort to cast a broad net on all possibilities, we computed all CAs less than 100 Mkm in the next ten years. The results of the computations are provided in Figure 5. We note that the asteroid 2002 GT falls in the bin with CA less than 10 Mkm, with 446 other NEOs.

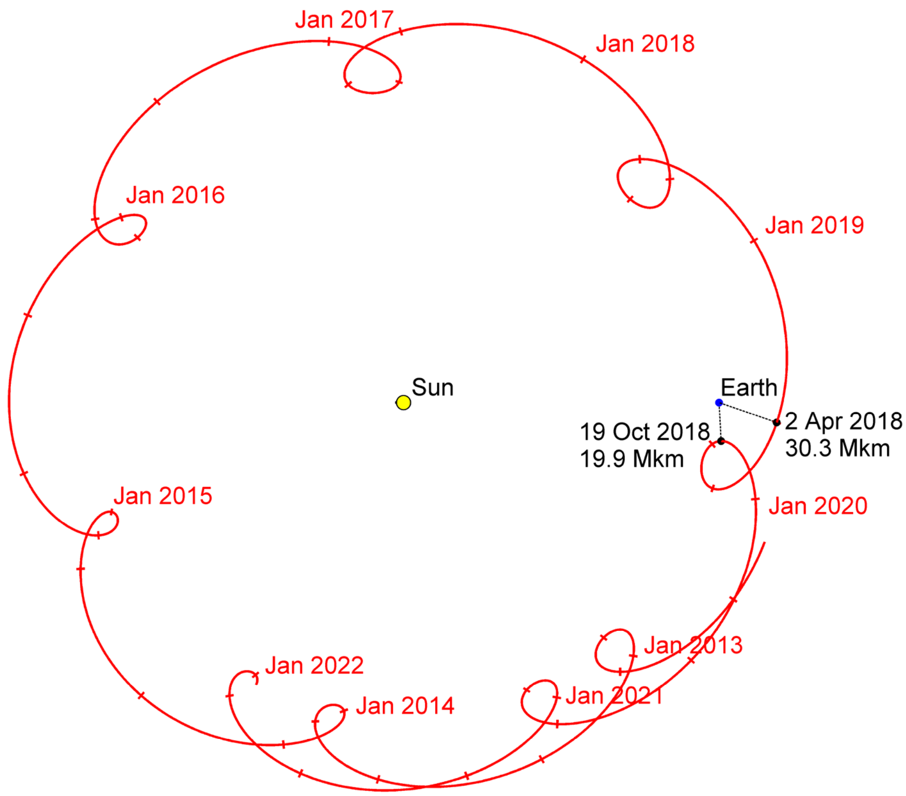



**Figure 4. DI Trajectory as Viewed from Earth-Fixed Rotating Frame, 3-Month Time Ticks.**

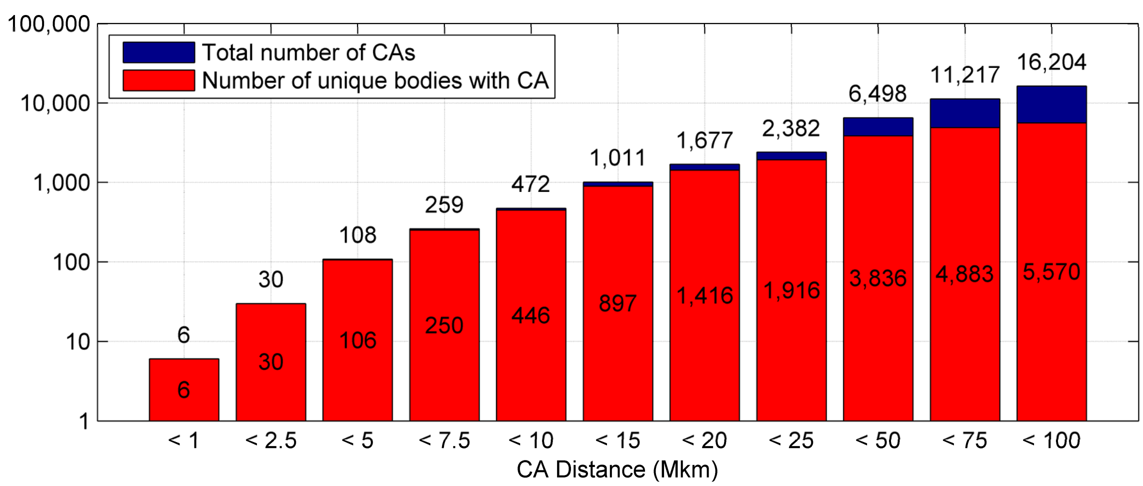



**Figure 5. NEO Close Approach Results for DI Spacecraft, August 19, 2010.**

### B. Targeting Close Approaches

Computing trajectories that target each of the CAs in Figure 4 would be a tremendous effort. Yet it was initially unclear which CAs should be targeted. It seemed intuitive that most CAs greater than 10 Mkm would be too large to target in 10 years and with only 12 m/s of propulsive $\Delta v$. However, depending on the sensitivity of the trajectory and when the maneuver is implemented, a CA greater than 10 Mkm may require less $\Delta v$ to target than a CA less than 1 Mkm. Therefore, to determine which CAs to target it is useful to define a maximum reachable distance, or MRD, for the spacecraft. The MRD defines how far from the nominal path the spacecraft can stray with 15 m/s. Targeting an NEO within this distance may require more $\Delta v$ than 15 m/s, but a target *outside* of the MRD is *guaranteed* to require more $\Delta v$. This implies that if we only search for and target CAs within the MRD, we can be certain we won't miss something. To define the MRD, we apply maneuvers from equally spaced points on a $\Delta v$-sphere at various epochs, and propagate the trajectories forward in a full-ephemeris model. For a given time, the MRD is the maximum distance between the resulting trajectories with the maneuver and the nominal, ballistic path. For DI, we computed the MRD using 50 equally spaced points on $\Delta v$-spheres of radius 15 m/s. The spheres are applied in 5-day increments along the trajectory, and spanning more than one revolution of the orbit. In Figure 6, each line corresponds to the maximum distance from the nominal path for each sphere. The MRD is the bold red line, or the topmost line at any given time. As clearly indicated by the figure, for maneuvers up until 2021, the MRD is less than 15 Mkm. Thus it is sufficient to target only the NEOs in Figure 5 with CAs less than 15 Mkm.

All CAs less than 15 Mkm were targeted using the mission design softwares MIDAS and Mystic.* MIDAS is an efficient optimizer that solves for minimum cost transfers as conic arcs using primer vector theory.[4] Mystic is a robust optimizer based on differential dynamic programming that solves for the transfers in a full-ephemeris model.[5] For both software, an estimate for the maneuvers is not required and therefore the solutions are not biased by the initial guess, and both software can allow for multiple maneuvers if necessary. Mystic found all the solutions that were computed in the MIDAS runs, plus many additional ones that were not found by MIDAS. A summary of the top six solutions from Mystic is reported in Table 1. As recorded in the table, there is no apparent correlation between the ballistic, non-targeted close approach distance and the $\Delta v$ necessary to target the asteroid.

The time-of-flight reported in Table 1 is measured from November 2010, when this study was conducted. The quantity in parenthesis in the $\Delta v$ column is the penalty for delaying the maneuver to after June 2011. For each option, the optimizer found that only one maneuver was required to target the flyby body. The parameter U is the uncertain value assigned by the Solar Systems Dynamic group at JPL. For U=0-2, the trajectory of the object is fairly well-defined, with 0 as the highest degree of certainty. Values 3-5 are marginal, and more data is necessary to determine the trajectory more precisely. The poorest degree of certainty is for objects with U=6-9, in which case the body must be rediscovered by a ground-based telescope before it could be reliably targeted by 100s of thousands of km. In the table, approach phase is the angle between the incoming hyperbolic asymptote and the sun-asteroid line. The sun-body-spacecraft angle at periapsis of the flyby is also useful for determining which geometries are favorable. While it is expensive to alter the approach phase angle, the sun-body-spacecraft angle can be adjusted with only a small penalty in the $\Delta v$ by varying the b-plane angle. We note that of the options presented in Table 1, only the top four fall within the $\Delta v$ budget allotted for the DI spacecraft.

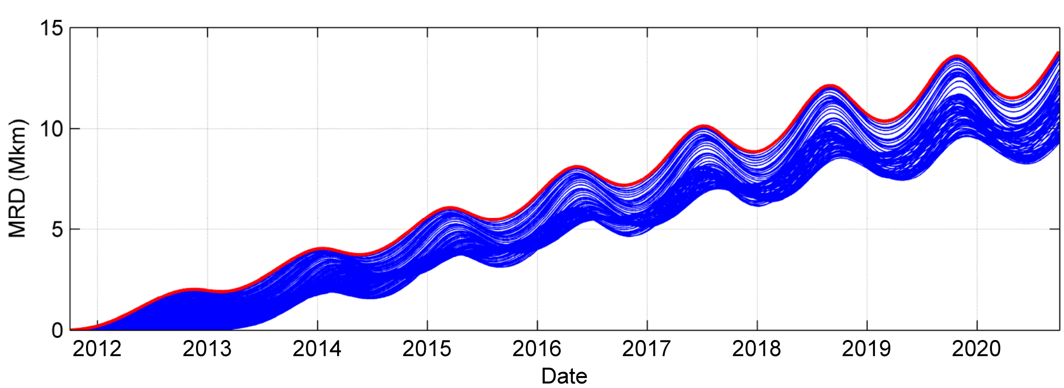



**Figure 6. Maximum Reachable Distance (MRD) for DI with $\Delta v$ = 15 m/s.**

* An alternative (and perhaps better) strategy only targets bodies inside the MRD at the time of the CA.

**Table 1. Top Six Search Results for DI NEO Flyby.**

| Object Name | U | Diam. (m) | Ballistic CA (Mkm) | TOF (yrs) | $\Delta v$ (m/s) | Maneuver Date | Encounter Date | $v_\infty$ (km/s) | Approach Phase (deg) | Sun-Body-s/c (deg) |
|---|---|---|---|---|---|---|---|---|---|---|
| 2007 TR24 | 7 | 275 | 3.2 | 7.5 | 9.7 (0.6) | 15 Feb. 2011 | 11 May 2018 | 22.4 | 179.0 | 90.7 |
| 2008 BE | 5 | 90 | 4.6 | 8.4 | 9.7 (0.0) | 22 Aug. 2011 | 21 Apr. 2019 | 8.5 | 135.1 | 86.5 |
| 2002 GT | 0 | 780 | 7.9 | 9.1 | 10.0 (0.2) | 27 Nov. 2010 | 4 Jan. 2020 | 7.1 | 138.0 | 131.7* |
| 2005 YA37 | 5 | 110 | 2.8 | 8.2 | 10.4 (0.4) | 11 May 2011 | 21 Jan. 2019 | 8.6 | 10.0 | 86.9 |
| 2006 EY | 8 | 30 | 1.8 | 3.7 | 14.0 (0.0) | 13 Jul. 2011 | 6 Aug. 2014 | 8.4 | 26.2 | 110.4 |
| 2000 CN101 | 0 | 4,450 | 5.9 | 3.9 | 17.8 (0.6) | 27 Nov. 2010 | 26 Oct. 2014 | 17.8 | 24.6 | 112.7 |

*Optimal trajectory for delaying maneuver to after June 2011 changed Sun-Body-s/c angle to 50.8 deg

## IV. Selection of 2002 GT

As of August 2011, the NEO ephemeris was updated and retargeted including 500 newly discovered objects not considered in the previous search. No new targets arose from the search, where in fact 2007 TR24 became unreachable with the new asteroid ephemeris. We note that the approach phase angle of 179 deg reported for 2007 TR24 in Table 1 would be impossible to navigate. The asteroid 2008 BE, although it is a desirable target due to its smaller size, represents a challenge for AutoNav considering its size and approach phase; furthermore the orbit is not well-known and only limited ground-based observation opportunities are available. The orbit of 2005 YA37 is also uncertain and the geometry of the flyby is one that might require reliance on batteries during AutoNav. For all intensive purposes, the asteroid 2006 EY is irretrievably lost (uncertainty U=8), and the $\Delta v$ to target the object is outside the budge for EPOXI. And finally, although the orbit for 2000 CN101 is well-known, the $\Delta v$ to target this asteroid is also too high.

Alternatively, the asteroid 2002 GT, which is also designated as a Potentially Hazardous Asteroid (Earth MOID = 0.015 AU, Absolute Visual Magnitude = 18.3), has a well-determined orbit and is roughly 800 ± 400 m in diameter. At present there is little more known about the nature of this object, but in mid-2013 it will pass near the Earth affording an exceptional opportunity for ground-based characterization. At this apparition, 2002 GT will be in range of the Arecibo planetary radar. In addition to Doppler measurements, radar delay observations with precisions as low as a few microseconds (range uncertainty less than 500 m) are expected. The asteroid will also be very bright, brighter than the 16$^{th}$ magnitude during the apparition, which will facilitate a host of observations at a variety of wavelengths. Light curve measurements across a wide range of viewing perspectives will reveal the rotation rate and ultimately lead to strong constraints on the shape and pole orientation. Light curve observations would also be likely to reveal whether the object is a binary asteroid. Visible and infrared spectra will constrain the mineralogy, taxonomy, albedo and size. Along with the radar observations, optical astrometry will further constrain the orbit, both to facilitate terminal guidance operations and to potentially reveal nongravitational forces acting on the asteroid. For these reasons, 2002 GT was selected as the eventual target for the DI spacecraft.

### A. Mission Overview

The minimum fuel trajectory to reach 2002 GT originally had one deterministic $\Delta v$ occurring October 2011 to achieve the encounter. However, there was serious concern about the estimates of the fuel remaining on the spacecraft, and it was strongly desired to obtain more data from the spacecraft to quantify the estimate. For this reason, the October maneuver was postponed one month while gathering and analysis was performed, and a two-maneuver strategy was adopted which incurred a small fuel penalty. The current baseline trajectory for EPOXI is shown in Figure 7. We briefly note here that on November 25, 2011, 00:00:00 UTC, the first of two maneuvers, an 8.8 m/s burn, was executed to put the spacecraft on course to encounter 2002 GT. The second maneuver of 1.9 m/s will be performed on October 4, 2012, and the spacecraft will encounter 2002 GT on January 4, 2020.

### B. Cruise and Approach Navigation

Navigation of the spacecraft for its cruise to 2002 GT is accomplished through standard ground-based processes.[8] Tracking data in the form of two-way Doppler and range is obtained through the Deep Space Network antennas. This radiometric observational data is compared against predicted values based on an initial guess at the trajectory parameters, and a least-squares estimation process is used to adjust the parameters until a converged solution is obtained. Once the current orbit during the tracking arc is obtained, the trajectory can be propagated into the future. If the predicted course deviates sufficiently from the planned one, correction maneuvers are performed to adjust the trajectory. These maneuvers are labeled "statistical" ones to differentiate from the "deterministic" maneuvers described above which define the reference trajectory; the statistical maneuvers are nominally zero and are used to correct navigational errors which build up over the mission.

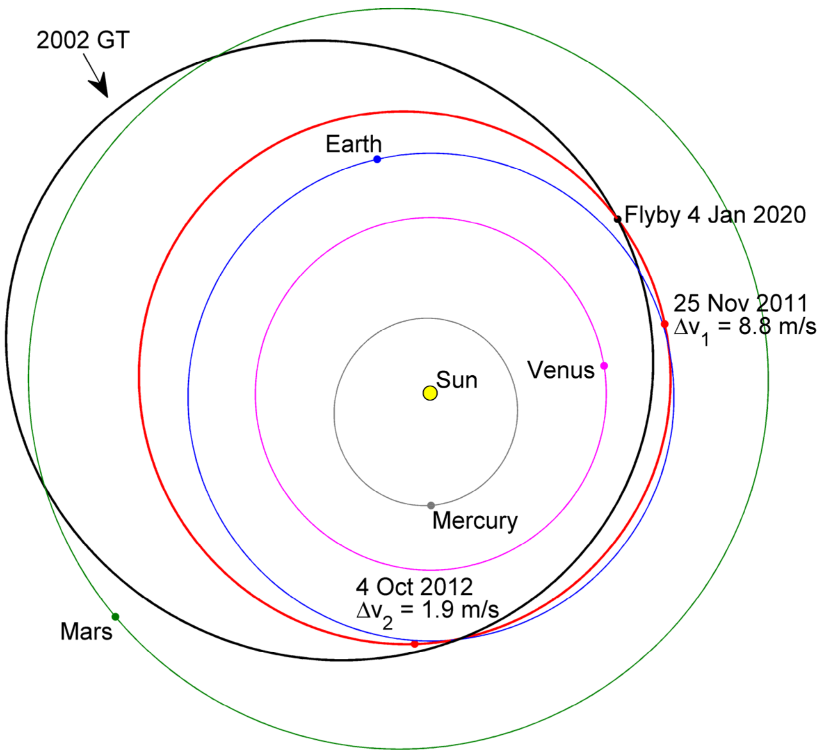



**Figure 7. Nominal Extended Mission for DI, Total Δ*v* = 10.7 m/s.**

The approach phase to a small body typically begins several months prior to encounter when the onboard camera detects the object for the first time. Then, the optical data are used to fine tune the trajectory relative to the target body itself; this is critical for small bodies because the a priori ephemeris errors (from ground observations) are not accurate enough for targeting close flybys. In the case of 200 GT however, the asteroid is so small that it may not be detected until a few days or even a few hours prior to encounter. For this reason, the terminal guidance for this encounter will be performed much as the Impactor did on DI, using Autonav.

### C. AutoNav Terminal Guidance & Flyby Imaging

One to two days prior to encounter, the best estimated trajectory of the spacecraft from ground-based navigation will be used to initiate the onboard AutoNav system. AutoNav will take a sequence of images of 2002 GT and use it to update the spacecraft's orbit relative to the asteroid. At predetermined times, the updated trajectory will be used to compute and execute maneuvers to target the flyby. The times for the maneuvers have not been optimized as of this writing, but it is envisioned that 3-4 will be needed. The first is used to remove any large ephemeris errors associated with the asteroid; the last could be performed as late as several minutes before closest approach to achieve the highest accuracy flyby. The encounter velocity will be 7.1 km/s and the approach phase angle is 138 deg. Since the phase angle is unfavorable for inbound imaging, the team has developed a novel flyby technique whereby the spacecraft will slew to an outbound imaging attitude after the terminal guidance imaging and maneuver activities will be completed, approximately two minutes prior to the encounter. Following the final maneuver, AutoNav will be placed in a "tracking" mode, where the orbit is continually updated based on continuing images, but the trajectory is not adjusted. Instead, the information is used by the Attitude Control System to know where to point the cameras through closest approach and departure. The technique is the same as used by the Flyby spacecraft on DI to track Tempel 1 and on EPOXI to track Hartley 2. (See Bhaskaran[2] for more details.) Simulations show that the onboard AutoNav capability is more than adequate to ensure a safe flyby at a distance of only 1 km. As indicated in Figure 8, guidance errors should be less than 250 m at 99% confidence.

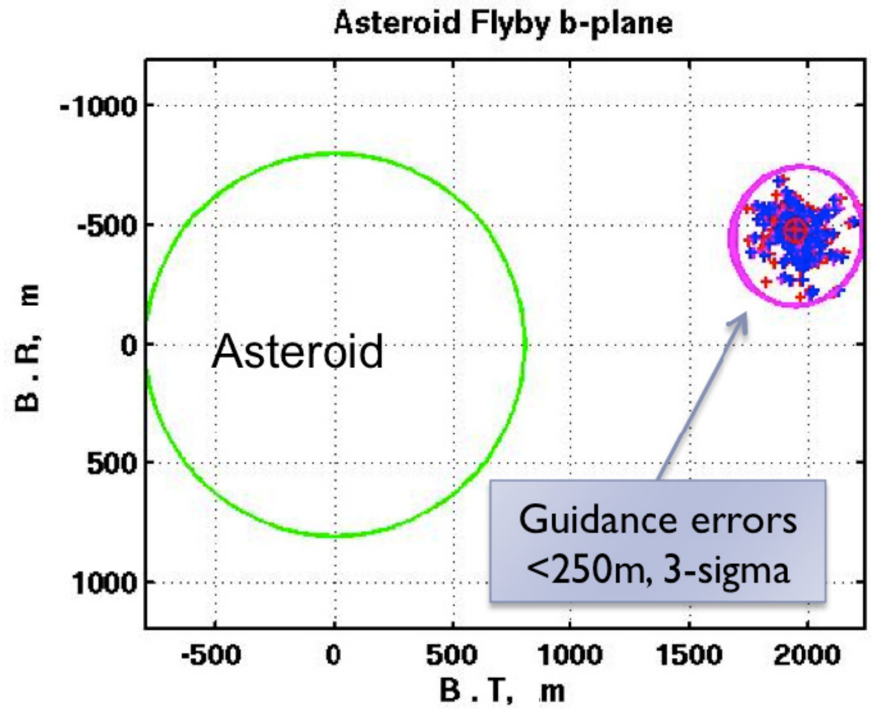



**Figure 8. Guidance errors expected during the fast, close flyby of asteroid 2002 GT.**

In addition to full-field images after the spacecraft has receded from the target, this flyby strategy will yield sub-meter imaging from the MRI and decimeter or better imaging from the HRI at closest approach (Figure 9). This resolution will rival that obtained by JAXA's Hayabusa spacecraft (approximately 1 cm/pixel[9]) during its exploration of asteroid Itokawa. The knowledge gained from this flyby will also be highly relevant to the human exploration program at NASA, where sub-kilometer near-Earth asteroids are continually attracting attention.

### D. Science Objectives

The science drivers for this investigation are numerous and range across the asteroid sciences. The geology of asteroids is still poorly understood, especially for sub-kilometer asteroids that are more susceptible to unexpected rotations caused by solar radiation pressure and possible binary formation through fission. The high-resolution imagery will reveal the crater and boulder distribution across the surface and will aid understanding of the distribution and nature of fines on the surface, including size sorting through seismic shaking or electrostatic dust levitation. The existence of features at the scale of the body will indicate the relative importance of cohesion. The surface slopes will indicate the extent to which the body's surface is relaxed and provide an indication of the mechanical properties of the surface material. The overall shape will allow inferences as to the fundamental nature of the body, whether it be monolithic, fractured or a rubble pile. If the object is a binary (about a 16% probability), the science returns would significantly increase, revealing the mass and density of the bodies and providing the first high-resolution imagery of a binary asteroid system. The 2013 observation opportunities have a good chance of revealing whether or not the system is binary.

## V. Conclusion

Of all the options available for the DI spacecraft, the sub-kilometer near-Earth asteroid 163249 (2002 GT) is the only viable option for a flyby in the next eight years with the estimated 18 m/s of $\Delta v$. The 2013 apparition of 2002 GT represents a unique opportunity to characterize the flyby target, which will aid interpretation of the high-resolution flyby imagery and aid planning and development of the flyby imaging sequence. Coordinating all of these observations, i.e., ensuring that all bases are covered and all data are reduced and published, will be a significant task for the science team.

The spacecraft executed its first maneuver to target 2002 GT on November 25, 2011, 00:00:00. The planned $\Delta v$ was 8.805 m/s and, from the OD solution using the post-TCM data, we achieved 8.813 m/s, or about a 0.01%

overburn. The spacecraft performed flawlessly, and the re-targeting will be complete with a second maneuver of 1.9 m/s scheduled for Oct. 4, 2012.

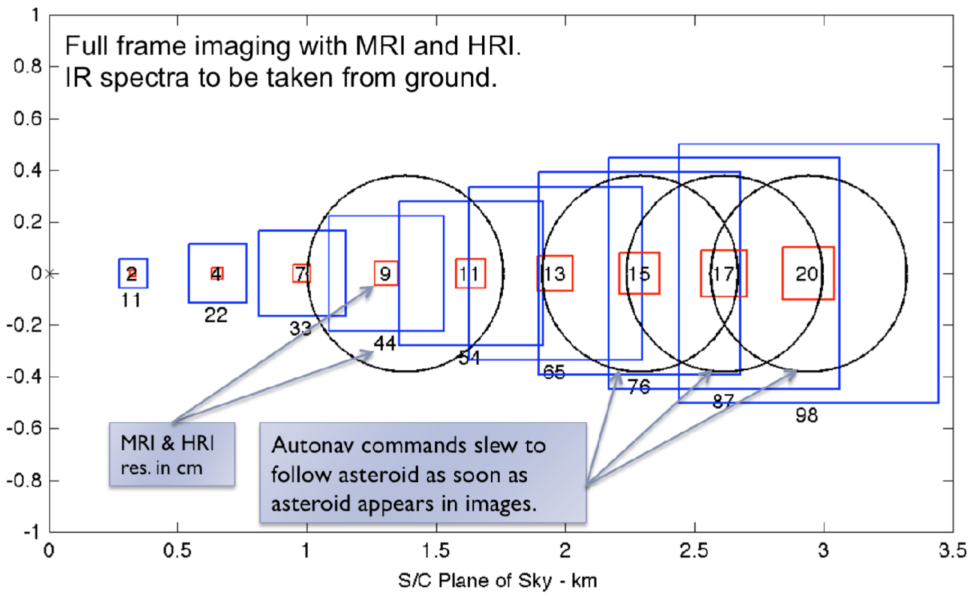



**Figure 9. Imaging scale expected from the flyby. The MRI fields are shown in blue with the associated image resolution below. The HRI fields are shown in red with the image resolution inside. The black circles represent the asteroid. Until acquisition, the camera has a fixed pointing and the asteroid sweeps across the field of view, as shown in the leftmost fields. Shortly after the asteroid is acquired post-flyby, the spacecraft slews to keep the asteroid in the field of view, as shown in the rightmost fields.**

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## References

[1]*Deep Impact Launch Press-Kit*. National Aeronautics & Space Administration, January 2005. [online publication], http://www.nasa.gov/pdf/103744main_presskit_121404.pdf, [retrieved 11 July, 2012].

[2]Bhaskaran, S., et al., "Navigation of the EPOXI Spacecraft to Comet Hartley 2," Paper AAS 11-486, *AAS/AIAA Astrodynamics Specialist Conference*, Girdwood, Alaska, July 31-August 4, 2011.

[3]JPL Horizons On-Line Ephemeris System, Solar System Dynamics Group, Jet Propulsion Laboratory, NASA. [online publication], http://ssd.jpl.nasa.gov/?horizons, [retrieved 11 July, 2012].

[4]Sauer, C. G., Jr., "MIDAS – MIssion Design and Analysis Software for the Optimization of Ballistic Interplanetary Trajectories." *Journal of the Astronautical Sciences*, Vol. 37, 1989, pp. 251-259.

[5]Whiffen, G. J., and Sims, J. A., "Application of a Novel Optimal Control Algorithm to Low-Thrust Trajectory Optimization," Paper AAS 01-209, AAS/AIAA Astrodynamics Specialist Conference, Santa Barbara, California, February, 11-14, 2001.

[6]Kubitschek, D. G., et al, "Deep Impact Autonomous Navigation: The Trials of Targeting the Unknown", AAS 06-081, *AAS Guidance and Control Conference*, Breckenridge, CO, February 2006.

[7]Abrahamson, M., Kennedy, B. M., Bhaskaran, S. B., "AutoNav Design and Performance for the EPOXI Hartley 2 Flyby, *SpaceOps 2012 Conference*, Stockholm, Sweden, June 2012.

[8]Wood, L. J., "Interplanetary Navigation," *Encyclopedia of Aerospace Engineering*, Vol. 5, edited by R. Blockley and W. Shyy, John Wiley & Sons, Ltd., Chichester, UK, 2010, pp. 3071-3084.

[9]Yano, H., et al, "Touchdown of the Hayabusa Spacecraft at the Muses Sea on Itokawa," *Science*, Vol. 312, No. 5778, pp. 1350-1353, 2006.